Rescue of a small declining population of Spanish imperial eagles

Miguel Ferrer [a,*], Ian Newton [b], Roberto Muriel [a]

[a] Department of Ethology and Biodiversity Conservation, Estación Biológica de Doñana (CSIC), C/Americo Vespucio s/n, 41092 Sevilla, Spain
[b] Centre for Ecology and Hydrology, Benson Lane, Crowmarsh Gifford, Wallingford OX10 8BB, United Kingdom

ABSTRACT

The Spanish imperial eagle (*Aquila adalberti*) is one of the most endangered raptors in the world. The population of Doñana National Park (south-western Spain) suffered a dramatic decline from 1990 on, after a long period of stability. The high adult mortality due to poisoning was the main cause of the decline, decreasing fecundity and biasing the offspring sex ratio to males due to a higher proportion of non-adult breeders in the population. In face of the imminent extinction, an urgent multi-action conservation plan was implemented in 2004. Supplementary feeding throughout the year with live wild rabbits was undertaken to prevent breeders from foraging outside the National Park and therefore reducing adult mortality by poisoning. Likewise, the population was reinforced with the release of young eagles (mainly females) by hacking techniques. After implementing the plan, the annual adult mortality decreased from 12% in the declining period to 2.1% during the recovery period. The lower adult mortality resulted in a lower population turnover and thus in an increasing average age of breeders (proportion of non-adult plumage decreased from 21.3% to 8.9%). Accordingly, the fecundity recovered to values close to those prior to decline (from 0.6 to 1.3 young/pair) and the sex ratio was balanced again (from 81% to 48% males). In fact, the predicted population persistence increased up to nearly six times after the application of the action plan. Therefore, the conservation actions applied were effective in a relatively short period and made possible the rescue of the threatened population from the extinction vortex.

Keywords:
Adult mortality
Doñana National Park
Food supplementation
Population management
Sex ratio
Spanish imperial eagle

1. Introduction

The Spanish imperial eagle (*Aquila adalberti*), with its global population of 340 pairs located exclusively in the Iberian Peninsula, is the most endangered bird of prey in Europe and one of the most threatened raptors in the world (Ferrer and Negro, 2004; BirdLife International, 2008). It is a large (2500–3500 g), sedentary and territorial bird of prey, with a low reproductive rate (average 0.75 chicks per pair per year), an immaturity period of 4–5 years, and an estimated maximum longevity of 21–22 years (Ferrer and Calderón, 1990). The species has three easily distinguishable plumage classes: (1) juvenile, with a tawny-coloured plumage that remains until the bird is 3 years old; (2) subadult, with dark patches over a tawny base, present in 4–5 year old birds; and (3) adult, that is predominantly dun-coloured with characteristic whitish markings, present in birds from the age of 5 years on. These differences are visible in the field and make the detection of a mixed-age pair (one member of the pair in non-adult plumage) easy and unequivocal.

Paired birds occupy territories, with a mean size of 1200 ha (range = 980–1870 ha; Ferrer, 2001), that are exclusive and vigorously defended throughout the year. In contrast, the behaviour of juvenile or subadult unpaired eagles (termed floaters) is radically different (Ferrer, 1993). Floaters move between temporary settling areas and return to the natal population continually during the early years of life (Ferrer, 1993).

The most intensively studied population of this eagle is in Doñana National Park (south-western Spain), where the 20,000 ha of suitable habitat holds a maximum of 16 pairs (Ferrer and Calderón, 1990; Ferrer and Donazar, 1996). This population at Doñana is separated from other breeding populations of this species, as the next closest breeding population of eagles is 150 km away (estimated interchange with other population of one eagle each generation; i.e., 16.4 years; see Ferrer and Calderón, 1990).

After a long period of numerical stability, the Doñana population started a dramatic decline after 1991. During 1990–2002 breeding numbers decreased annually by an average of 6% (Ferrer and Penteriani, 2008). In addition, fecundity declined from a mean value of 0.75 young per pair per year during the stable period to 0.59 during the 1990–2002 decline. At the same time, the average annual sex ratio of young changed from 50% to 78% males. Despite a supplementary feeding program started in 1991, providing food to breeding pairs close to the nest during the breeding period, it was not possible to change the declining trend. In 2004, in face of this urgent situation, we studied the causes of this decline to suggest conservation actions to avoid local extinction.

* Corresponding author. Tel.: +34954466700; fax: +34954621125.
E-mail address: mferrer@ebd.csic.es (M. Ferrer).

A large increase in annual adult mortality, due to an increase in poisoning in hunting areas surrounding the National Park, was identified as the main factor explaining this decline (Ferrer and Penteriani, 2008; Ferrer et al., 2009). The use of poison (mainly cholinesterase inhibiting agricultural insecticides as carbamates and organophosphates) aimed at generalist predators increased when a new disease, pneumonic hemorrhagic virus, reduced wild rabbit populations (Villafuerte et al., 1994; Ferrer and Negro, 2004; Hernández and Margalida, 2009). With a low rabbit density, eagles were forced to explore areas outside the National Park, where they came into contact with poisoned baits. Poisonings accounted for more than 54% of the 51 breeding eagles found dead in the period 1990–2002, increasing average annual adult mortality from 6.1% to 12.0%. This high adult mortality indirectly caused changes in fecundity (Allee effect; Ferrer and Penteriani, 2008) and the sex ratio of nestlings (Ferrer et al., 2009).

The effect on fecundity was due to the long breeding cycle in the eagles, which lasts for some 8 months (Ferrer, 2001). Assuming that the probability of death is uniform throughout the year and that both parents are necessary during the whole cycle, with a 6% rate of adult mortality the population of Doñana National Park lost one pair during the breeding season each year on average. In consequence, fledgling production of the entire population is expected to change only from 11.3 to 10.53 because the effect of adult mortality on fecundity is negligible. Nevertheless, in a population of 15 pairs with an annual adult mortality of 12.01%, the predicted adult mortality rate is 3.6 per year and the expected fecundity is 0.6 fledglings per pair. Therefore, as adult mortality increases its effects on fecundity also increases. High mortality rates for adults also depress floater availability causing an increasing difficulty to replace a lost mate in the breeding population. A delay in a substitution could result in the loss of the breeding season that year. High adult mortality and low floater availability both facilitated an Allee effect (Ferrer and Penteriani, 2008).

Due to the high turnover in territory holders, as a consequence of high adult mortality, the proportion of breeders in non-adult plumage increased. It is known that in the case of the Spanish imperial eagle (Ferrer et al., 2009), as in other bird species (e.g., Red-winged Blackbird [*Agelaius phoeniceus*]; Blank and Nolan, 1983; Wandering Albatross [*Diomedea exulans*]; Weimerskirch et al., 2000), younger breeders produced more chicks of the smaller (cheaper) sex, males in the case of the eagle (male weight/female weight = 0.83). This in turn produced a sex-ratio deviation at the nestling population level of this Spanish imperial eagle population affecting seriously the population viability (Ferrer et al., 2009).

Calculating Vortex simulations, using the high mortality rates of adult birds, low fecundity, and distorted sex ratio of chicks in 2004, estimated mean time to extinction for the population was 11.5 years, with a 100% probability of extinction in 100 years (Ferrer et al., 2009).

In light of these results, a new management program was implemented from 2004 with the aim of reducing the adult mortality, restoring the sex ratio of nestlings and recovering the imperial eagle population of Doñana. In order to avoid the risk of eagles exploring areas outside the National Park and to provide secure food for them, within the breeding territories, we built fences around ½ ha areas stocked with live rabbits provided throughout the year. The aim was not to increase fecundity by food provisioning, but to reduce the movements of adult eagles outside the National Park, and hence the risk of poisoning. At the same time, a radio-tracking program to detect eagle mortality and educational work programs for hunters were implemented.

It was expected that a decrease in adult mortality would lead to increased fecundity. Also a more balanced sex ratio among chicks would be expected due to an increase in the mean age of breeders (Ferrer et al., 2009). Nevertheless, population reinforcement with young eagles, mainly females coming from other populations, was also undertaken and during 2005–2009, 15 young eagles were released in Doñana National Park using hacking techniques (Muriel et al., 2011).

In this paper, we analyze whether those actions have successfully rescued this declining population of eagles, by reducing adult mortality, recovering a 1:1 sex ratio, increasing fecundity and population size, and decreasing significantly the risk of extinction. For this analysis, we consider three different periods: the 1976–1991 period during which the population was in stable mode, the 1992–2003 period during which population was in a dramatic decline, and the 2004–2011 period during which the new management techniques were applied (Table 1).

2. Methods

The data used in this study were obtained from the Doñana Biological Station archives and collected in the field by one of the authors (M.F.) from 1985 to 2011 inclusive. The whole National Park area was surveyed at the beginning of each breeding season to determine if pairs were present on breeding territories. Surveys covered territorial establishment, nest selection and courtship periods (January-February). The sedentary behaviour of this species, and its tendency to call repeatedly, greatly facilitates the detection of pairs on territory. It is therefore likely that all breeding attempts were detected, as were pairs that did not breed. We considered a breeding attempt as successful when the nestlings reached the age of 50 days (i.e., the age of ringing). During 1984–1999, sex was determined by applying a discriminant function analysis including forearm and tarsus length (Ferrer and De le Court, 1992). Since 2000, we also used a different molecular method, taking a blood sample when ringing the nestlings, and using the cellular fraction to sex the eagles (Ellegren, 1996). Analyses were carried out in the molecular ecology laboratory of the Doñana Biological Station.

In order to evaluate the ultimate effect of management techniques on the persistence of the population, we conducted simulation analyses. Analyses of population viability as a tool to evaluate management techniques have been used extensively (Nilsson, 2003; Naujokaitis-Lewis et al., 2008; Soutullo et al., 2008; Duca et al., 2009; García-Ripollés and Lopéz-Lopéz, 2011). Here we used the Vortex simulation software (Vortex, version 9.72; Lacy et al., 2005) to compare variation in persistence time before and after the application of the recovery plan, including two scenarios, with and without releases of young eagles by hacking. We used previously published estimates of fecundity and mortality parameters (Ferrer and Calderón, 1990; Ferrer et al., 2004; Ferrer and Penteriani, 2008; Ferrer et al., 2009), as well as field data from the last 8 years of the study period (Table 2). We performed 1000 replicates of each scenario for 100 years of simulation. Assumptions used for the PVA included a monogamous breeding system, a stable age distribution, and breeding by 100% of adults. Reproduction was assumed to occur at 4 years of age, and the maximum age of reproduction was set to 22 years (Ferrer and Calderón, 1990). As

Table 1
Demographic parameters of the population during the three studied periods (1976–1991, stability; 1992–2003, decline; 2004–2011, recovery). Last rows shows parameter values for the recovery period including the released young eagles.

Periods	Adult mortality (%)	Immature breeders (%)	Fecundity	Sex ratio of nestlings
1976–1991	6.07	3.294	0.815	0.401
1992–2003	12.01	21.34	0.559	0.812
2004–2011	2.11	8.888	1.059	0.508
With releases	2.11	8.888	1.294	0.484

Table 2
Summary of input parameters used in the Vortex simulations for the scenarios before the implementation of the action plan (1992–2003) and after (2004–2011). Values were obtained from previous studies as well as from field data (see Methods for further references).

Parameter	Mean (SD)
Reproductive system	Monogamy
Age of first breeding	4 years
% Breeding	100
Fecundity	
1992–2003	0.559 (0.422)
2004–2011	1.059 (0.823)
2004–2011 (with released bids)	1.249 (0.911)
Sex ratio	
1992–2003	0.812
2004–2011	0.508
2004–2011 (with released bids)	0.484
Annual mortality rate	
First year juveniles	0.6 (0.878)
Unpaired eagles	0.257 (0.296)
Paired eagles (1992–2003)	0.120 (0.132)
Longevity	22 years

the density of the population was very low during the simulated period (Ferrer and Donazar, 1996), we assumed a density independent model. To account for environmental stochasticity, we subtracted the expected binomial variance from the total variance estimated from the field data (Ferrer et al., 2009).

3. Results and discussion

The number of breeders found dead per year was significantly different among the three periods (GLM Poisson distribution, log link; Wald statistic=35.03, $P<0.001$), with the lowest values during the management period. Sixteen adults were found dead in the 16-year period 1976–1991, the period of population stability (1.00 adults per year). Taking into account that the Doñana population consisted of 15 pairs in those years and the relative isolation of the population (only one among the 106 recoveries of ringed eagles in Doñana area was ringed outside Doñana), this gives an annual adult mortality of 3.6%, equivalent to slightly more than half the mortality rate estimated by age-class sightings during these years (6.1%; Ferrer and Calderón, 1990). During 1992–2003, a 12-year period of population decline, 17 adult eagles were found dead (1.42 adults per year). Considering the population size, and assuming that the probability of finding a dead eagle was the same in both periods, we could estimate an annual adult mortality rate of 12.01% during 1992–2003. During 2004–2011, an 8-year period, only two adult eagles were found dead (0.25 adults per year). Again considering that the probability of finding a dead eagle was the same among periods and taking into account the population size, annual adult mortality could be estimated at 2.1%. In particular, the number of breeders found poisoned decreased significantly from the 12-year period of decline, with nine eagles poisoned, to only one during the 8-year recovery period (exact binomial one-tailed test for expected mortality rates of 0.6:0.4, $P=0.046$).

The proportion of birds breeding in non-adult plumage differed significantly among periods, (GLM normal distribution, log link; Wald statistic=21.68, $P<0.001$), with low values in the first period, a substantial increase during the decline period, followed by a recovery to low values after management was implemented. Fecundity values also showed significant differences among periods (GLM normal distribution, log link; Wald statistic=14.96, $P<0.001$). High values were recorded in both the stable and recovery periods and very low values during the declining period. Significant differences in sex ratio among the three periods were found (GLM normal, log link; Wald statistic=16.07, $P<0.001$), with nearly 50% of males during the stable period, followed by a significant increase in the number of males during the period of decline, returning to normal values after the implementation of the conservation actions (Table 1).

As predicted (Ferrer and Penteriani, 2008), after a decrease in the annual mortality of breeders, and its recovery to normal values, the previous Allee effect detected in this population disappeared and fecundity reached values typical for an increasing population at low density (Ferrer and Donazar, 1996; Ferrer et al., 2006, 2008). The growth of the number of pairs and fecundity in the

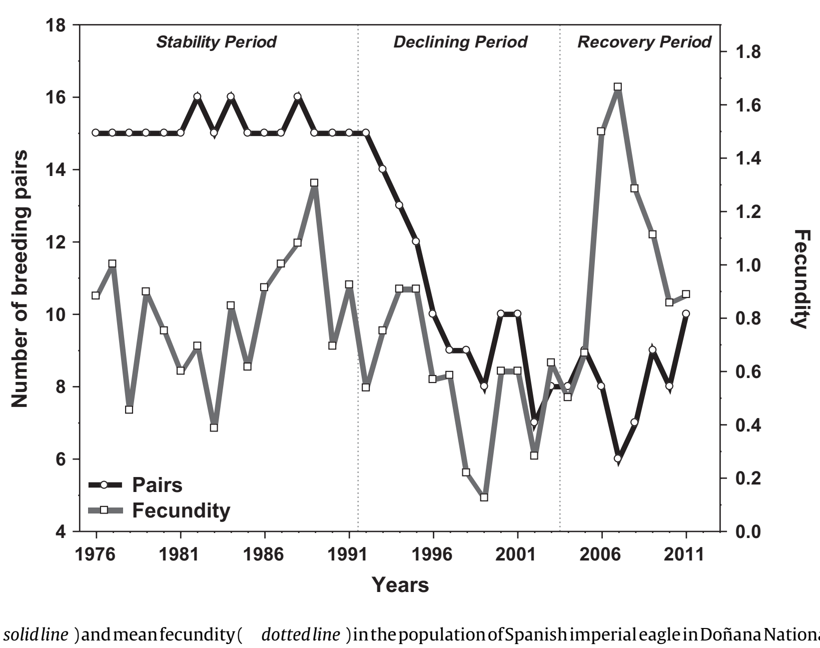

Fig. 1. Number of breeding pairs (*solid line*) and mean fecundity (*dotted line*) in the population of Spanish imperial eagle in Doñana National Park (south-western Spain). During the stability period (1976–1991) the population remained close to the carrying capacity level (16 pairs) with stable mean fecundity. In the declining period (1992–2003), the number of breeding pairs dropped off as a result of increasing adult mortality by poisoning, which in turn led to the reduction of fecundity (Allee effect). In 2004, a multi-action recovery program was applied. Fecundity showed an immediate and noticeable increase followed by a delayed population recovery.

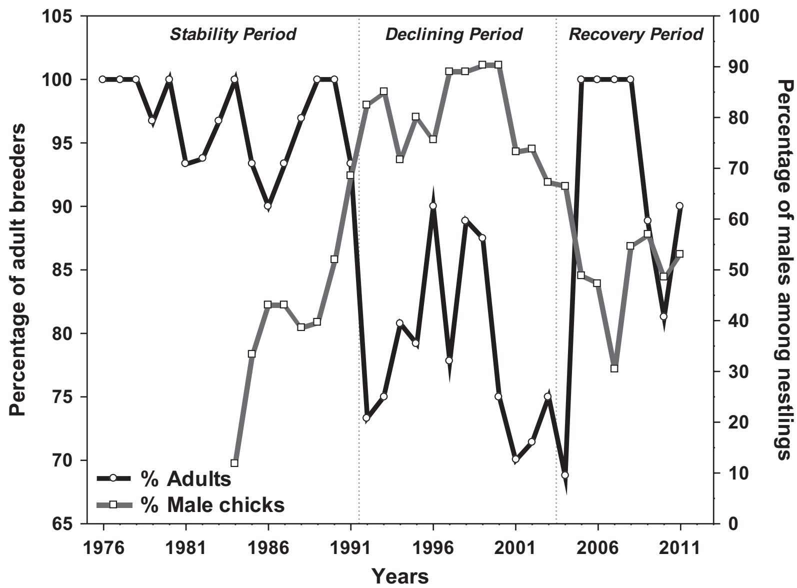

Fig. 2. Variation during the three periods considered in the proportion of breeders in adult plumage (*solid line*) and in the sex ratio of the offspring (*dotted line*). Significant negative relationship between these two variables was found ($r = -0.587$, $P = 0.001$). Sex ratio is represented using the smoothed values of a 3 years period in order to avoid large fluctuation due to small sample sizes.

Table 3
Main simulation outputs (using Vortex) and population extinction probabilities before the application of the management plan (1992–2003) and after (2004–2011). In this last case we considered separately simulations not including young eagles released by hacking (without releases) and other including these juveniles (with releases). A high increase in mean time to extinction in the last two cases was evident.

Scenario	Offspring sex ratio (%)	Extinction probability	Mean time extinction (SD)	r (SD)
Declining period 1992–2003	81	1.000	11.5 (6.39)	−0.140 (0.325)
Without releases 2004–2011	50	0.766	58.2 (33.26)	−0.027 (0.308)
With releases 2004–2011	50	0.718	65.5 (36.48)	−0.019 (0.310)

population shows a clear recovery process in response to management. Reproductive rate changed in advance of the number of breeding pairs (Fig. 1). This lag was expected because the usual age of first breeding in the Spanish imperial eagle is 4–5 years (Ferrer et al., 2004). First fecundity values in the recovery period correspond to a few pairs in the population (only six) breeding in the very best territories where they were able to reach very high fecundity records in absence of high adult mortality (see Ferrer and Donazar, 1996). As soon as population size started to recover, increasing the number of breeding pairs, fecundity values returned to normal values for this species, higher anyways than those recorded during the declining period.

After the recovery of normal values in breeder mortality, the turnover rate of the population must also return to normal values, allowing an increase in mean age of breeders and, consequently, a recovery of the 1:1 sex ratio among chicks. The relationship between the percentage of breeders in adult plumage and the ratio of male chicks over the studied period was highly significant ($r = -0.587$, $P = 0.001$; Fig. 2). This result strongly support our previous hypothesis suggesting that immature breeders tend to produce more chicks of the smaller (cheaper) sex, males in the case of the Spanish imperial eagle (Ferrer et al., 2009) as in other birds (Blank and Nolan, 1983; Weimerskirch et al., 2000). As soon as the proportion of adult breeders increased after the application of management, the proportion of female chicks increased, recovering a 1:1 proportion with males.

Results of simulations showed that the application of new management techniques after 2004 had a great impact on the theoretical persistence time of the population (Table 3). The probability of extinction estimated within a 100 year period changed from 100% before application of the plan to 76.6% without considering the translocated young eagles, or to 71.8% including these released young, that is to say a decrease of 28.2% in the risk of extinction. The estimated mean time to extinction changed from 11.5 years before implementation of the recovery plan to 58.2 years after implementation without allowing for the introduced young, or to 65.5 including the released young. Results showed that both actions would have significant effects but the decrease of adult mortality was by far more important. In fact, time to extinction increases by 506% only due to reduction in adult mortality and consequent increases in fecundity and sex ratio (i.e., without considering the increases in fecundity due to nestlings coming from other populations that were released by hacking, neither their effect on sex ratio). Summing up the effect of additional young females released by hacking, time to extinction increases by 570%, which is only 64 points more.

These results show that, in a relatively short period, the management procedures were effective in increasing significantly the persistence time for the population. Recovery of the 1:1 sex ratio after the proportion of adult breeders had returned to normal values strongly support our previous predictions (Ferrer et al., 2009), confirming the relationship between breeder age and sex of chicks. The decrease in adult mortality was the main reason for the recovery of the population, and the construction of the fenced areas, inside the eagles territories, stocked with live wild rabbits throughout the year seemed to prevent the eagles from foraging beyond their territories outside of the National Park, thus reducing the risk of poisonings.

Owing to the relative isolation of this population, any increase in adult mortality could not be compensated by immigration (Ferrer and Penteriani, 2008). For this reason, in 2002 a reintroduction program in a different area was started, with the objective of connecting the Doñana population with the eastern populations of

Andalucía, and thereby increasing the probability of interchange between Doñana and other populations (Muriel et al. 2011). The first successful breeding in the reintroduction area occurred in 2010, when two young were raised (Muriel et al. 2011). By 2012, there were up to five occupied territories in the area. Therefore, it seems that, in the near future, the Doñana population could be more secure thanks to this new population.

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